Aggregation rules for surface parameters in global models

W. J. Shuttleworth, Z.-L. Yang, M. A. Arain

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W. James Shuttleworth, Zong-Liang Yang, and Muhammed Altaf Arain

Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ 85721

Abstract

Aggregation rules are derived for calculating the effective value of parameters that determine the exchange of momentum and energy between the land surface and the atmosphere at the length scales used in General Circulation Models (GCMs). The derivation involves starting from theories that link parameters relevant at grid scale and patch scale, and then imposing the limitations necessarily present when models are operated in a free-standing, predictive mode. The application of these rules is illustrated by example for the case of the Biosphere-Atmosphere Transfer Scheme (BATS). Remotely sensed global maps of land cover classes at 1 km × 1 km pixel scale for North America, South America, and Africa are used with these new aggregation rules to calculate area-average values of parameters for the 3° × 3° grid mesh used in the National Center for Atmospheric Research Community Climate Model. There are significant differences between the parameters calculated using aggregation rules and the values selected on the basis of the dominant vegetation cover in each grid, this being the selection procedure conventionally applied with BATS.

Introduction

Providing adequate area-average (or aggregate) representation of heterogeneous land cover in meteorological models is a challenge that has concerned hydrometeorologists for more than a decade. One way to describe heterogeneous vegetation is to make a calculation for each separate patch of vegetation. This is the so-called 'mosaic' approach, in which separate models are used to estimate the fluxes for each patch at each time step, and an appropriately weighted average value is then taken (e.g. Koster and Suarez, 1992). The alternative approach requires less computer time. It involves using a single model of the surface exchanges with the values of vegetation-related parameters chosen to represent the area average or 'aggregate' behaviour of the heterogeneous vegetation mix present in the area represented. In this second case the problem reduces to defining appropriate values for the required area-average parameters.

There has been substantial progress in specifying area average parameters on two fronts, one being essentially empirical and the other theoretical. The empirical approach (e.g., Mason, 1988; Blyth, *et al.*, 1993; Noilhan and Lacarrere, 1995; Arain *et al.*, 1996, 1997) is to create a coupled surface-atmosphere model, to postulate hypothetical rules (often called 'aggregation rules', Shuttleworth, 1991) to give parameters applicable at larger scales by combining the parameters that control surface exchanges for small plots of uniform land cover, and then to test whether calculated values of parameters given by applying these rules give adequate representation when substituted into a one-dimensional area-average representation of exchanges. The method usually involves making model runs for a range of meteorological conditions and, ideally, the model is initiated, calibrated, and validated using field data.

The theoretical approach (e.g. l'Homme, 1992; McNaughton, 1994; Raupach, 1995; and Raupach and Finnigan, 1995, 1997) is to adopt the equations that are accepted as reasonable descriptions of surface-atmosphere exchanges for small plots of uniform land cover (especially the Penman-Monteith equation), to assume that such equations can also be used to describe the area-average behaviour of heterogeneous cover, and to derive theoretical equations that link the parameters required at large scales with those that apply for individual small plots. The resulting equations given by this theoretical approach are exact (within the limits of the equations assumed to apply at small scales) but, unfortunately, as will be discussed later, they cannot be routinely applied to a model which is operating in free running predictive mode using a single one-dimensional description of grid-average surface exchanges because this requires information that is not then available.

In this paper the need to reconcile these two alternative approaches is addressed. Specifically, starting from the relationships derived using the theoretical approach, we impose the limitations present in a predictive model to create approximate aggregation rules for three of the most important vegetation-related surface parameters (i.e., zero plane displacement, aerodynamic roughness and minimum surface resistance) which are, as far as possible, consistent with theory. To give the present discussion relevance, we place the derivation in the context of the Biosphere-Atmosphere Transfer Scheme (BATS: Dickinson *et al.*, 1986, 1993).

The following section provides an overview of modern aggregation theory. Section 3 describes the derivation of theory-based aggregation rules, while Section 4 describes the application of these new aggregation rules in the case of BATS and compares the results with parameter values selected on the basis of the default dominant vegetation cover in each grid.

Aggregation Theory

The work of Wieringa (1986), Mason (1988), McNaughton (1994), Raupach (1995) and Raupach and Finnigan (1995, 1997) together provide an accurate specification of the mathematical procedures by which aggregate vegetation-related parameters relevant at the subgrid (patch) scale can be combined to give a description of area-average surface fluxes. The foundation used to specify these mathematical procedures (McNaughton, 1994) is that area-average scalar fluxes must be conserved, and that the model used to describe area-average land-surface-atmosphere exchanges at a grid scale must have the same form as the model used to describe such land-surface-atmosphere exchanges at a patch scale.

In the case of momentum exchange, applying these two criteria gives the result:

$$\frac{1}{R_{a,M}} = \left[\sum_i \frac{w_i}{r_{a,M,i}}\right] \tag{1}$$

where $R_{a,M}$ and $r_{a,M,i}$ are the grid-average and patch-average aerodynamic resistances, respectively, and w_i is the fractional area of patch i in the grid square. This equation, when applied in neutral conditions, has been used to define the grid-average aerodynamic roughness length in terms of the aerodynamic roughness length applicable to individual patches (Wieringa, 1986; Mason, 1988; Shuttleworth, 1991; Arain *et al.*, 1996, 1997).

In the analyses given by McNaughton (1994), Raupach (1995), and Raupach and Finnigan (1995; 1997), and in most advanced land-surface parameterization schemes, the model used to represent surface energy partition is in essence the Penman-Monteith equation (Monteith, 1965). Therefore the vegetation-related parameters that matter at both patch scale and grid scale are the aerodynamic resistance and the surface resistance (and, if considered appropriate, the radiative resistance) used in that equation.

To simplify the present description, the results of Raupach (1995) in the situation which he designated 'the simple case' are summarised below. In this case, the aerodynamic resistances between the canopy and the overlying atmosphere for latent and sensible heat are assumed equal, and long-wave radiative coupling between canopy level and the near-surface atmosphere is deemed negligible. Without these assumptions, the mathematics are more complex, but are identical in concept. In the simple case, Raupach (1995) expressed the Penman-Monteith equation applicable at grid scale and patch scale in the form:

$$E = \frac{\Delta R_a A + \rho\lambda D}{\Delta R_a + (R_a + R_s)} \tag{2}$$

and

$$E_i = \frac{\Delta r_{a,i} A_i + \rho\lambda D_i}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})} \tag{3}$$

respectively. In the above equations, E and E_i are the grid-average and patch-average latent heat fluxes, respectively; A and A_i are the grid-average and patch-average available energy, respectively; R_a and $r_{a,i}$ are the aerodynamic resistances for energy fluxes at grid scale and patch scale, respectively; R_s and $r_{s,i}$ are the surface resistances applicable at grid scale and patch scale, respectively; ρ is air density; λ is the latent heat of vaporisation of water; D [$= q_{sat}(\theta) - q$] and D_i are the potential saturation deficits of the ambient air at a specified level, with θ the potential temperature and q specific humidity at that height; and Δ [$= (\lambda/c_p)\, dq_{sat}/dT$] is the dimensionless slope of the saturation specific humidity $q_{sat}(T)$ as a function of temperature T, where c_p is the isobaric specific heat of air.

By applying the McNaughton (1994) criteria to Eqns (2) and (3), Raupach (1995) derived the relationships between resistances required to give a match of fluxes between the grid scale and patch scale representations, thus:

$$R_a = \frac{R_d}{A}\sum_i \frac{w_i A_i r_{a,i}}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})} \tag{4}$$

and

$$R_s = \frac{R_d}{A}\sum_i \frac{w_i A_i r_{s,i}}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})} \tag{5}$$

where

$$R_d = \left[\sum_i \frac{w_i}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})}\right]^{-1} \tag{6}$$

Although the theory just summarised is elegant and accurate, unfortunately it cannot be applied in the context of free standing, predictive climate models, except in the trivial case that the model makes explicit representation of the surface energy and water balance for each component patch (in which case there is no need to make an aggregate representation). Otherwise, at any particular time step for which the model is required to make a grid-average, aggregate, description the values of A_i are (by definition)

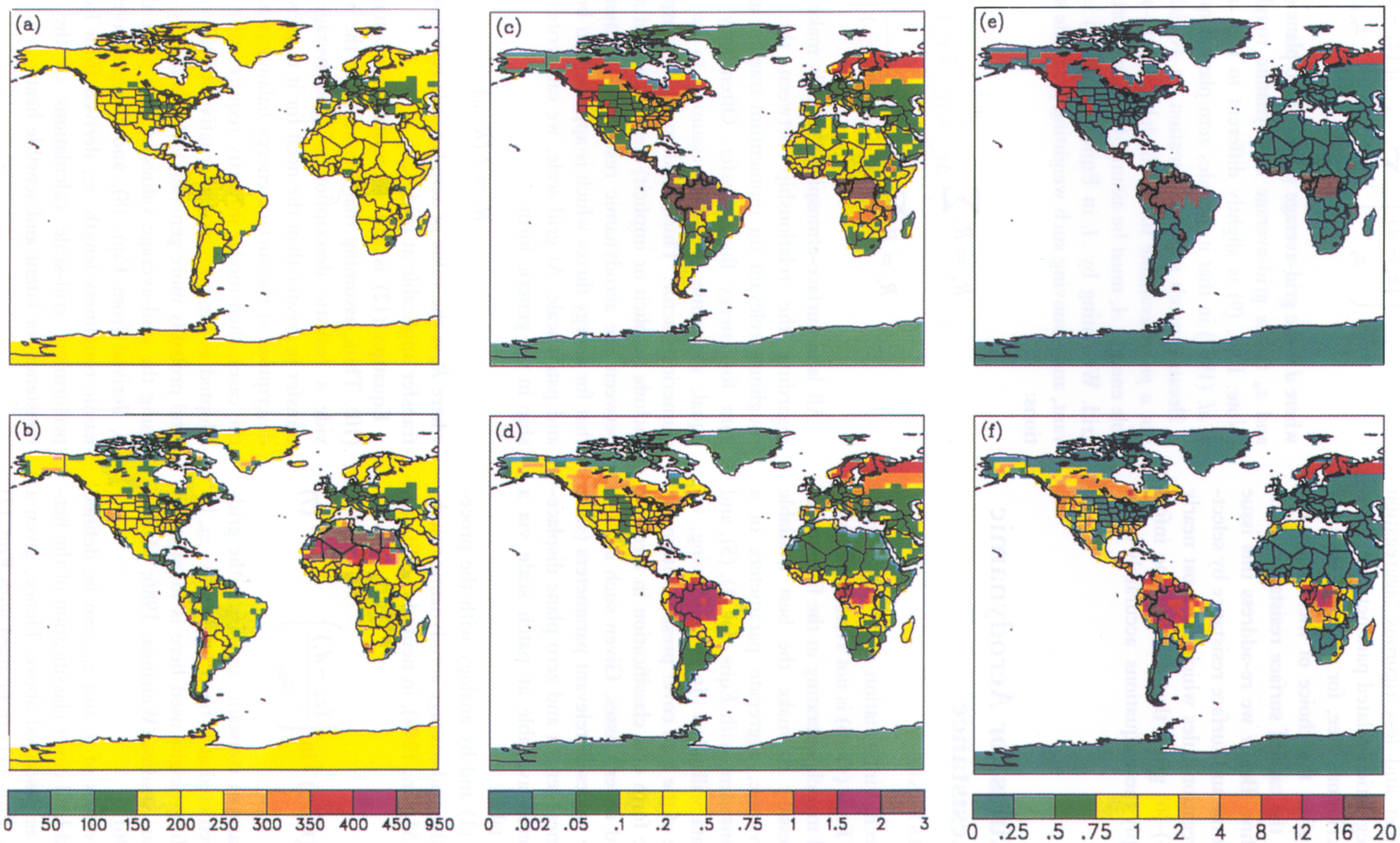

Fig. 1 *Values of vegetation-related parameters in the Biosphere-Atmosphere Transfer Scheme as interfaced to version 3 of the National Center for Atmospheric Research Community Climate Model calculated at 3° × 3° grid mesh. (a) and (b) show minimum stomatal resistance (in s m^{-1}), (c) and (d) show aerodynamic roughness length (in m), and (e) and (f) show zero plane displacement (in m). (a), (c), and (e) illustrate values for dominant land-cover class, while (b), (d), and (f) illustrate values given by applying aggregation rules. In the case of values calculated using aggregation rules, only values for North and South America and Africa are relevant, and values appropriate to dominant cover are reproduced elsewhere.*

unknown, as are the resistances $r_{a,i}$ and $r_{s,i}$, because they depend on unknown, patch-specific atmospheric variables and soil moisture. Recognition of this problem has forced the definition of simpler and less rigorous 'aggregation rules' for combining vegetation-related parameters in grid-average aggregate descriptions (see, for example, Arain *et al.*, 1997). However, often the choice of these rules has been arbitrary and, in the case of surface resistance, difficult to justify and define. Below we re-address this issue in the case of aerodynamic and surface resistance by selecting the choice of aggregation rules which are most nearly equivalent to Eqns (4)–(6) given that some of the information required to apply these equations accurately is not available.

Aggregation Rules for Aerodynamic and Surface Resistance

AERODYNAMIC RESISTANCE

Because the patch-specific information required to make detailed application of Eqns (4)–(6) is not available for predictive, meteorological models operating in the free-standing mode, it is necessary to make the best available assignment of grid-average, aggregate parameters in a manner which is as consistent with Eqns (1), (4), (5), and (6) as the available data will allow. In the following, we assume that the nature of the land cover present within the grid is available in the form of a classification in terms of the model-specific land cover classes. Given such a patch scale classification, the values of relevant parameters (such as aerodynamic roughness length and zero plane displacement) can be considered available at patch scale via a model-specific lookup table.

Starting from Eqn. (1) and by analogy with the procedure used to evaluate the grid-average aerodynamic roughness (Weiringa, 1986; Mason, 1988), in neutral conditions, we can assume that:

$$r_{a,M,i} = (\kappa^2 U_b)^{-1} \ln^2\left(\frac{(z_b - d_i)}{z_{0,i}}\right) \tag{7}$$

where κ is the von Karman constant, and U_b is the grid-average wind speed predicted at a 'blending height', z_b, by the model. The blending height used here is identical to that defined in previous studies (Weiringa, 1986; Mason, 1988; Arain *et al.*, 1996).

The patch-specific values of d_i and $z_{0,i}$ can be defined from a remotely sensed land cover classification of the heterogeneous landscape as described above. Hence, given a prescribed value of U_b, Eqn. (1) can be used with Eqn. (7) to provide a value for $R_{a,M}$, the required aerodynamic resistance for momentum exchange at grid scale. In practice, this is equivalent to applying the two aggregation rules:

$$d = \sum_i w_i d_i \tag{8}$$

$$\ln^{-2}\left(\frac{(z_b - d)}{z_o}\right) = \sum_i w_i \ln^{-2}\left(\frac{(z_b - d_i)}{z_{o,i}}\right) \tag{9}$$

where d is the grid-average value of zero plane displacement, and z_o is the grid-average aerodynamic roughness length. [Note: Eqn. (9) is slightly different to that used in Arain *et al.* (1997) in that it includes zero plane displacement].

Because patch scale information on available energy is not *a priori* available to the model, the grid-average available energy, A, must be assumed uniform across the model grid. Weighting by A_i in Eqns (4) and (5) is thus irrelevant, and removing such weighting gives the simpler equations:

$$R_a = R_d \sum_i \frac{w_i r_{a,i}}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})} \tag{10}$$

$$R_s = R_d \sum_i \frac{w_i r_{s,i}}{\Delta r_{a,i} + (r_{a,i} + r_{s,i})} \tag{11}$$

All land-surface-atmosphere models make assumptions regarding the relationship between the aerodynamic roughness relevant for momentum transfer and that relevant for energy flux transfer. Often they are assumed equal; sometimes they are assumed to be related by a numerical factor. Thus, land-surface-atmosphere models include (explicit or implicit) specification of a relationship between the aerodynamic resistance for momentum and that for energy fluxes which is applicable at both grid scale and patch scale. At grid scale, we can write this relationship in the generic form:

$$R_a = F(R_{a,M}) \tag{12}$$

where R_a is the value of aerodynamic resistance for energy transfer applicable at grid scale.

Equation (12) is not necessarily consistent with Eqn. (10). Thus, assuming that the need for the model to provide a realistic description of grid-average momentum transfer is greater than the need for it to provide a precise description of the surface-energy balance (which is usually the case), then model integrity requires that Eqn. (12) be adopted as the preferred alternative. In the case of BATS (and probably more generally), this is merely equivalent to using the grid-average values of zero plane displacement, d, derived from Eqn. (8), and the grid-average aerodynamic roughness length, z_o, derived from Eqn. (9) when performing grid-scale calculations of the aerodynamic resistance for latent and sensible heat.

SURFACE RESISTANCE

In principle, Eqn. (11) can be used to make an estimate of the surface resistance, R_s, applicable at grid scale so long as it is possible to provide estimates of $r_{a,i}$ and $r_{s,i}$ for each patch of land cover in the grid. McNaughton's (1994) requirement that the models used at grid scale and patch scale have the same form requires that the aerodynamic resistance for energy transfer applicable at patch scale, $r_{a,i}$, be given by an equation which is equivalent to Eqn. (12), that is by:

$$r_{a,i} = F(r_{a,M,i}) = F\left((\kappa^2 U_b)^{-1} \ln^2\left(\frac{(z_b - d_i)}{z_{0,i}}\right)\right) \quad (13)$$

This is equivalent to using the patch-specific values of zero plane displacement, d_i, and the patch-specific aerodynamic roughness length, $z_{o,i}$, when making patch-scale calculations of the aerodynamic resistance for latent and sensible heat, i.e., (in neutral conditions):

$$r_{a,i} = (\kappa^2 U_b)^{-1} \ln^2\left(\frac{(z_b - d_i)}{z_{0,i}}\right) \quad (14)$$

The generic form of the surface resistance, $r_{s,i}$, used in many land-surface-atmosphere models (including BATS) is:

$$r_{s,i} = \frac{r_{s(\min),i}}{l(L_i)s(S, D, M_s, T, \ldots)} \quad (15)$$

where $r_{s(min),i}$ is a constant specific to the land cover class present in patch i; the function l describes the relationship between surface resistance and the leaf area index, L_i, of the patch (often $l = L_i$); and s is a stress factor that is used here to represent the influence on surface resistance of all other relevant environmental variables. As suggested in Eqn. (15), such variables might include the downwelling solar radiation, S; the saturation vapour deficit, D; the soil moisture in the rooting zone, M_s; and the ambient air temperature, T; etc. [Note: In the case of the BATS, dependence on D is indirect and is imposed through a restriction on the upper limit of transpiration flux.]

In the absence of any patch-specific values for the variables S, D, M_s, and T, etc., it is necessary to assume that their grid-average values apply in Eqn. (15) and, consequently since these vary, that the stress factor, s, is equal to unity for each patch of vegetation. It is convenient also to define the grid-average value of the leaf area factor, thus:

$$l_{grid} = \sum_i w_i l(L_i) \quad (16)$$

Further, if Eqns (6) and (11) are to be used to prescribe the grid-average value of $R_{s(min)}$ for each continental grid square, it is necessary to choose a representative value for U_b, the wind speed at the blending height, to calculate $r_{a,i}$ in Eqn. (14).

Equations (6), (11), (15), and (16) can be combined into the form:

$$R_{s(\min)} = l_{grid} \frac{\sum_i \left[\frac{w_i \rho_i}{(\Delta + 1) + \rho_i}\right]}{\sum_i \left[\frac{w_i / r_{a,i}(U_b)}{(\Delta + 1) + \rho_i}\right]} \quad (17)$$

where

$$\rho_i = \frac{r_{s(\min),i}}{l(L_i) r_{a,i}(U_b)} \quad (18)$$

or, in neutral conditions and where $l(L_i)=L_i$ (as is the case for BATS):

$$\rho_i = \frac{(\kappa^2 U_b) r_{s(\min),i}}{L_i \ln^2\left(\frac{(z_b - d_i)}{z_{0,i}}\right)} \quad (19)$$

Application of Aggregation Rules to BATS

In this section we illustrate the application of the above-defined aggregation rules in the case of BATS as used in version 3 of the NCAR Community Climate Model (CCM3 Kiehl *et al.*, 1996). The primary need is for globally-available information on land cover class. Such data are now being provided by merging remotely sensed data with *in situ* information. A second requirement is for typical values of the meteorological variables that appear explicitly or implicitly in Eqns (7), (9), (17) and (19).

LAND COVER DATA

The land cover data we use in this analysis were obtained from the Earth Resources Observing System Data Center Distributed Active Archive Center (Loveland *et al.*, 1991, 1997; EDC DAAC). These data were generated jointly by the U.S. Geological Survey, the University of Nebraska-Lincoln, and the European Commission's DG Joint Research Centre at 1 km resolution as a global data base from Advanced Very High Resolution Radiometer data spanning April 1992 through March 1993. The land cover data are provided for an extensive range of different land cover classes, but they are also provided for subgroups of land cover classes which correspond to those used in certain well recognised land surface parameterization schemes. It is the reclassified data appropriate for BATS which are used in the present analysis. The data are exploratory in nature and, at this writing, they are only available for the continents of North America, South America, and Africa. The present analysis is therefore necessarily restricted to these three continents. However, the procedures are applicable globally; the general conclusions are likely also to be applicable to other continents.

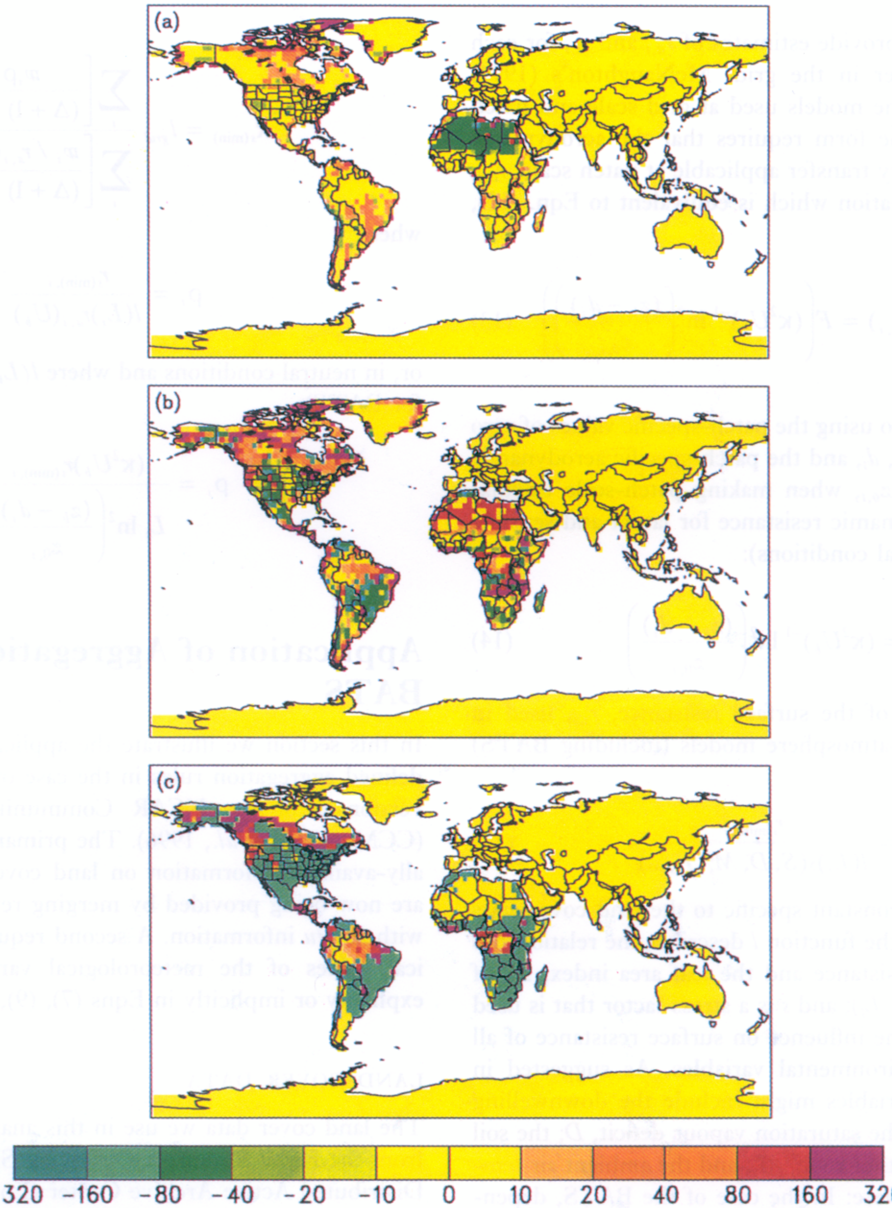

Fig. 2 *Difference between BATS-relevant vegetation parameters for the single dominant vegetation cover hitherto assigned in CCM3 and the aggregate value derived from the USGS/EDC data with a 3° × 3° (CCM3) grid, expressed as a percentage of the aggregate value for (a) minimum stomatal resistance, (b) aerodynamic roughness, and (c) zero plane displacement.*

REPRESENTATIVE VARIABLES AT BLENDING HEIGHT

Applying even the simplified form of aggregation theory described above—in which the requirements for subgrid scale knowledge of meteorological variables and soil moisture have been removed—still requires *a priori* knowledge of grid-average weather variables at an assumed blending height.

Clearly, the first need is to specify the blending height below which the aggregate parameters are assumed to apply, but in fact the lowest modelled level is the practical choice. In CCM3, this level is typically around 60 m above the ground over continents, but the value changes with season and location because the height is related to surface pressure. Such changes are small (typically ±5m), and they have little impact on the calculation of aggregate surface parameters. Nonetheless, for reasons of consistency with the other global fields required in the calculation (described below), monthly average values of blending height were computed for every grid square from an 11-year run of CCM3 with surface parameters specified to correspond to the dominant land cover in each grid square, this being the default choice of parameters for BATS. The default dominant cover in each CCM3 grid is assigned based on vegetation maps (for details see Dickinson *et al.*, 1993).

Calculation of aggregate values for z_o, d, and $R_{s(min)}$ requires knowledge of wind speed and (to allow the calculation of Δ) temperature and pressure at the blending height. Moreover, the computation of $R_{s(min)}$ from Eqns (17) and (19) requires an estimate of L_i, the leaf area index for the grid square. In the case for BATS, the leaf area index of each component cover is a function of T_g, the modelled temperature of the deep soil layer (in °K), and of $L_{i,max}$ and $L_{i,min}$, the prescribed, patch-specific maximum and minimum leaf area index, respectively. Thus:

$$L_i = L_{i,\max} + [L_{i,\min} - L_{i,\max}].[1 - S'] \quad (20)$$

where

$$S' = S(T_g) \quad S(T_g) > 0$$
$$= 0 \quad S(T_g) \le 0 \quad (21)$$

and

$$S(T_g) = 1 - 0.0016T_{g,\max}^2 \quad (22)$$

where $T_{g,max}$ = (298 – T_g) or zero, whichever is greater.

In the present study, the required values of transient variables were prescribed in the same way as was the blending height, i.e., the soil temperature and the wind speed, air temperature, and pressure at the lowest model level computed for every grid square and averaged for each calendar month from an 11-year run of CCM3 made using surface parameters which corresponded to the default dominant land cover in each grid.

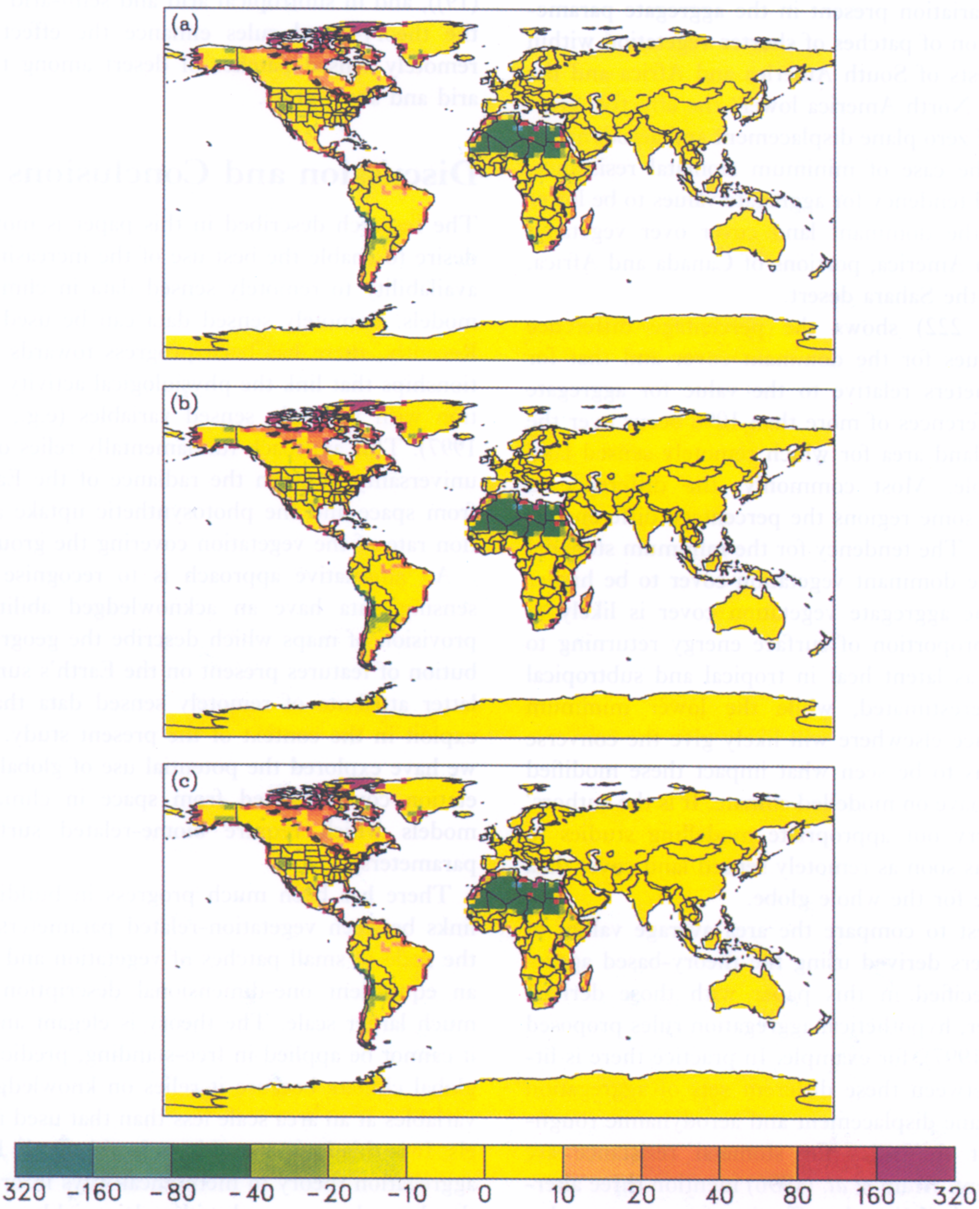

Fig. 3 *Difference between the calculated aggregate value of minimum stomatal resistance given by (a) a linear aggregation rule, (b) a reciprocal aggregation rule, and (c) the average of these last two averages (Arain et al., 1997) and the theory-based rules specified in this paper, expressed as a percentage of this latter aggregate value.*

CALCULATED PARAMETERS

Figure 1 (p. 219) shows values of vegetation-related parameters in each CCM3 grid for both the default dominant land cover and from aggregation rules (i.e., from Eqns (8), (9),(17) and (19)). Figures 1a and 1b show minimum stomatal resistance, 1c and 1d show aerodynamic roughness length, and 1e and 1f show zero plane displacement. Figs 1a, 1c, and 1e illustrate values for dominant land cover class, while Figures 1b, 1d, and 1f illustrate values given by aggregation rules. In the case of values calculated using aggregation rules, only values for North and South America and Africa are relevant, and values appropriate to dominant cover are reproduced elsewhere.

The most obvious general feature visible in Fig. 1 is the greater spatial variation present in the aggregate parameters. The inclusion of patches of shorter vegetation within the tropical forests of South America and Africa and the boreal forests of North America lowers the effective grid-average values of zero plane displacement and aerodynamic roughness. In the case of minimum stomatal resistance, there is a general tendency for aggregate values to be lower than those for the dominant land cover over vegetated regions of South America, portions of Canada and Africa, but higher over the Sahara desert.

Figure 2 (p. 222) shows the percentage difference between the values for the dominant cover and that for aggregate parameters relative to the value for aggregate parameters. Differences of more than 10% occur over the majority of the land area for which remotely sensed land cover is available. Most commonly, the difference is 20–80%, but in some regions the percentage difference is greater than this. The tendency for the minimum stomatal resistance for the dominant vegetation cover to be higher than that for the aggregate vegetation cover is likely to mean that the proportion of surface energy returning to the atmosphere as latent heat in tropical and subtropical regions is underestimated, while the lower minimum stomatal resistance elsewhere will likely give the converse effect. It remains to be seen what impact these modified parameters will have on modelled climate. It is the authors' intention to carry out appropriate modelling studies to investigate this as soon as remotely sensed land cover data become available for the whole globe.

It is of interest to compare the area average values of surface parameters derived using the theory-based aggregation rules specified in this paper with those derived using the simpler, hypothetical aggregation rules proposed by Arain *et al.* (1997), for example. In practice there is little difference between these different sets of aggregation rules for zero plane displacement and aerodynamic roughness length but the rules for stomatal resistance are markedly different. Arain *et al.* (1996) mention three alternative rules for calculating the effective area-average value of minimum stomatal resistance, these being linear averaging, reciprocal averaging, and the average of these last two averages (for greater detail see Arain *et al.* 1997).

Figure 3 (p. 223) shows the difference between the aggregate value of minimum stomatal resistance given by (a) a linear aggregation rule, (b) a reciprocal aggregation rule, and (c) the average of these last two averages (Arain *et al.*, 1997) and the value given by applying the theory-based rules specified in this paper expressed as a percentage of this latter aggregate value. Clearly there are significant differences between the theory-based set of rules suggested here and the earlier hypothetical rules in the case of stomatal resistance when differences as large as 80% can occur. The effect of applying theory-based aggregation rules is most noticeable at high latitudes where the new rules capture the effect of seasonality in leaf area index on the minimum stomatal resistance (Eqns (17) and (19)), and in subtropical arid and semi-arid regions where the theory-based rules enhance the effect of including remotely sensed patches of desert among those of semi-arid and short grass.

Discussion and Conclusions

The research described in this paper is motivated by the desire to enable the best use of the increasing global scale availability to remotely sensed data in climate prediction models. Remotely sensed data can be used in two ways. Recently, there has been progress towards building relationships that link the physiological activity of the vegetation with remotely sensed variables (e.g., Sellers *et al.*, 1997). This approach fundamentally relies on an assumed universality between the radiance of the Earth measured from space and the photosynthetic uptake and transpiration rate of the vegetation covering the ground.

An alternative approach is to recognise that remote-sensing data have an acknowledged ability to aid the provision of maps which describe the geographical distribution of features present on the Earth's surface. It is this latter attribute of remotely sensed data that we seek to exploit in the context of the present study. In particular, we have explored the potential use of global maps of vegetation cover derived from space in climate prediction models which require biome-related surface exchange parameters.

There has been much progress in building theoretical links between vegetation-related parameters applicable at the scale of small patches of vegetation and parameters in an equivalent one-dimensional description applied at a much larger scale. The theory is elegant and precise, but it cannot be applied in free-standing, predictive models of global climate because it relies on knowledge of transient variables at an area scale less than that used in global models. It is this issue we address in this study by simplifying aggregation theory in methodical ways in order to remove the dependency on subgrid scale variables.

By using the Biosphere-Atmosphere Transfer Scheme as an example of the surface models used in General Circulation Models, we conclude that it is indeed possible to rewrite the most advanced form of aggregation theory so that it depends only on grid-average variables but still retains the basic interplay between surface and aerodynamic controls on surface fluxes. This simpler form of aggregation theory still requires knowledge of representative grid-average values of meteorological variables at a blending height in the atmosphere which, for practical reasons, is the height of the lowest modelled level. In this study, these transient variables were estimated as monthly average values from an initial model run in which the surface parameters were specified assuming parameters applicable for the single, most common vegetation cover present in the grid. When the simplified version of the aggregation theory is applied to BATS using remotely sensed land cover data (at this time only available for North America, South America, and Africa), there are significant differences between the aggregate values of aerodynamic roughness, zero plane displacement and minimum stomatal resistance, and the equivalent values for the dominant biome in each grid square. Broadly speaking, the ensuing changes are such that the evaporation calculated by BATS is likely to increase in vegetated tropical and subtropical regions, but likely to decrease elsewhere.

Recognising the growing accessibility of relevant remote-sensing data on land cover class and the likely increasing availability of such data gathered under the upcoming Earth Observation System, our general conclusions are (a) that it is feasible to use these new data in global climate prediction models operating in free-standing predictive mode using (an albeit simplified version of) aggregation theory; (b) that to do this is a comparatively simple process; and (c) assuming that the results we obtained with BATS over three continents are more generally applicable, that there is a consequent and noticeable change in the effective, area-average value of parameters which control surface energy partition.

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